TRANSFER CALIBRATION OF HEAT FLUX SENSORS AT NIST

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Reprinted from the National Heat Transfer Conference, 32nd ASME. Proceedings. Volume 7. HTD-Vol. 345. American Society of Mechanical Engineers (ASME). 1997, Kaminski, D.; Smith, A. M.; Smith, T. F., Editors, 81-88 pp, 1997.

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

HTD-Vol. 345, National Heat Transfer Conference
Volume 7
ASME 1997

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ABSTRACT

An ongoing program at the National Institute of Standards and Technology (NIST) aims to develop competence in calibration of high heat-flux sensors and to provide a source of calibration traceability to other users and manufacturers. This paper describes the experimental methods developed using high power lasers and blackbody radiation as radiant sources to transfer the calibration from a primary radiometric standard to the heat flux sensors up to 100 kW/m². An electrical substitution radiometer, with calibration traceable to the NIST High Accuracy Cryogenic Radiometer (HACR), is used as a transfer standard. A graphite tube high temperature blackbody is used as a broadband radiant source to transfer the calibration from the transfer standard to the heat flux sensors. Preliminary results of calibration of a Schmidt-Boelter heat flux sensor using the methods developed are presented. Further plans to extend the calibration capability up to 200 kW/m² are discussed.

NOMENCLATURE

- h: Planck's constant
- I: current
- k: coverage factor
- P: power
- X: distance between blackbody exit and gage
- λ: wavelength
- ν: wave number

INTRODUCTION

A well-known approach to the calibration of high heat flux sensors is to use radiation heat transfer to provide the desired level of irradiance at the sensor surface. High temperature blackbodies are excellent sources (Olsson, 1991) for this purpose since the broadband radiation from the blackbody aperture closely resembles Planckian distribution. Knowing the temperature of the blackbody and other geometric parameters, the heat flux level at the sensor surface can be determined theoretically. The temperature of the blackbody is measured by a pyrometer or a thermocouple with calibration traceable to a national standard. Knowing the temperature, the radiation exiting from the blackbody aperture is calculated using the Stefan-Boltzmann equation. It is desirable to conduct the sensor calibration using radiation heat transfer in vacuum to minimize heat loss due to convection cooling effects at the sensor surface.

The heat flux at the sensor surface is a fraction of the radiation from the blackbody aperture and is determined by the geometrical view factor (Siegel and Howell, 1992) between the sensor and the radiating aperture. The accuracy of the heat flux calculation at the sensor surface can be easily determined knowing the uncertainties in temperature measurement and the location of the sensor from the blackbody radiating aperture. The method tends to become more accurate as the distance between the sensor and the blackbody increases since the uncertainties due to aperture uniformity and the calculation of view factors will be smaller. This method, often referred to as "absolute calibration", relies entirely on the blackbody environment. It is possible to improve the accuracy of calibration by accounting for radiation from the enclosure surrounding the aperture and the sensor.

An alternate, but often more difficult to implement, method is to calibrate heat flux sensors with high power laser radiation. Sensors calibrated directly for photon or heat flux, using laser radiation can serve as reference standards which can be used to transfer calibration to other sensors using blackbody radiation or other radiant sources. This approach, referred to as "transfer calibration", eliminates some of the uncertainties associated with absolute calibration, and less expensive blackbodies can be employed as transfer sources for routine calibration.

It is necessary that the transfer standard must be capable of absorbing the total incident radiant flux. Cavity type electrically calibrated radiometers are best suited for this purpose. The absolute cavity radiometers work on the principle of equivalence between thermodynamic heating and electrical heating. The electrical voltage and current can be measured very precisely, thus enabling calculation of the power required to keep a resistor at certain temperature. Such electrically calibrated radiometers (ECR) have been developed to a high degree of precision and are commercially available. They exhibit excellent long term stability which is a prime requirement for their use as a transfer standard for calibrating other sensors. In principle, the electrically calibrated radiometer measurements are considered absolute. The main sources of error in the electrical substitution radiometers are non-equivalence, lead heating, and non-spectral flatness. Characterization to account for these sources of error requires calibration with respect to a higher accuracy primary standard. Such further characterization will help keep track of long term drift and other uncertainties.

To meet the current needs of the U.S. science and industry, the National Institute of Standards and Technology (NIST) is involved in developing methods and competence in the calibration of high heat flux sensors. Facilities employing different modes of heat transfer; radiation, convection and conduction, are under development to calibrate sensors up to 100 kW/m^2. *The Optical Technology Division at NIST is* implementing radiative methods of transfer calibration traceable to radiometric standards. The experimental methods developed use high power lasers to calibrate transfer standard radiometers, and high temperature blackbodies for broadband calibration of heat flux sensors. This paper gives a description of the radiative facilities developed, preliminary calibration results of a heat flux sensor, and plans for further development.

METHODOLOGY

The methodology adapted in calibrating heat flux sensors at NIST is schematically shown in Fig. 1. The objective is to establish a calibration technique directly traceable to a radiometric standard by measurement of the radiant flux in a laser beam underfilling the radiometer aperture rather than heat flux calculation based on temperature measurements. The method relies on accurate determination of the ECR aperture to convert radiant flux to irradiance response.

Primary and Working Standards

The primary standard (Gentile et al., 1996) in the U.S. for optical radiation measurement is the High Accuracy Cryogenic Radiometer (HACR). The HACR is an electrically calibrated radiometer with a relatively large cavity (time constant ≈ 240 s) and operates at cryogenic temperatures (≈ 5 K). The temperature rise in the cavity due to optical power absorption is compared with the electrical power required for the sa temperature rise by resistive heating. Operation at cryoge temperatures considerably reduces the thermal radiation effects due to surroundings and heat dissipation in the wires. These factors lead to highly accurate measurements of the incident optical radiation, with a relative expanded uncertainty of 0.02 % (coverage factor k = 2) at about 1mW power, compared to the much higher uncertainties of about 1 % for conventional room temperature electrically calibrated radiometers.

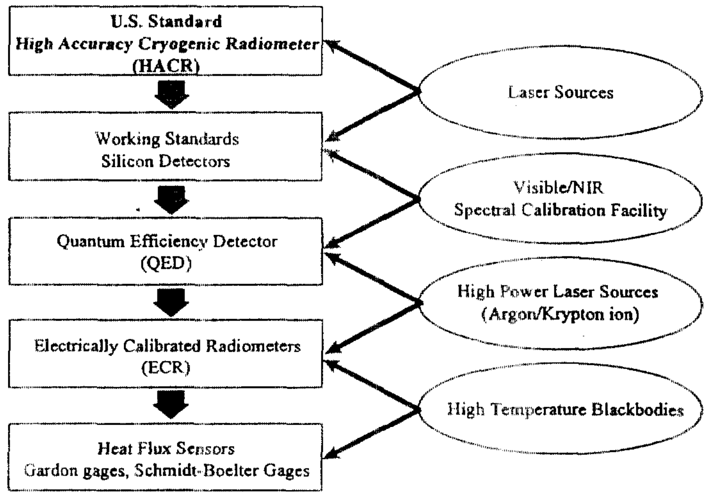

Fig. 1. Heat flux sensor calibration methodology

Routine use of HACR for calibration of detectors is not recommended due to its complex and time consuming test procedure. In many practical situations, the high accuracy of HACR is not required due to other much larger uncertainties in measurements. Hence, transfer detectors or trap detectors calibrated in HACR are used to calibrate working standard photodiodes in a Spectral Comparator Facility (SCF) which is an incoherent source and monochromator. Reference (Larason, et al., 1996) gives the details and principle of operation of the Visible to near infrared Spectral Comparator Facility (Vis/NIR SCF) used for this purpose. The relative expanded uncertainty (k =2) of measurements in the Vis/NIR SCF is about 0.22 %.

Heat Flux Measurement Standards

The basic radiometric standard (Zalewski and Duda, 1983) used for heat flux measurements is a quantum efficiency detector (Model QED-200[1]). It is an absolute standard in the visible range (360 nm to 800 nm). It is essentially a trap detector constructed with a number of silicon photodiodes having nearly 100 % quantum efficiency. The silicon

[1]Model QED-200, Visible wavelength reference standard, United Detector Technology, Hawthorne, CA. Certain commercial equipment, instruments, or materials are identified in this pare to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment are necessarily the best available for the purpose.

photodiodes are connected in parallel to sum the photocurrents f the individual diodes. With the QED-200 model used in the present measurements, three silicon photodiodes are arranged in such a way to give a total of five absorbing surfaces in the light path. This arrangement results in almost complete absorption of the incident photon flux and the output photocurrent of the detector is proportional to the incident flux. The output current (I) is directly proportional to the input power (P), and is given by, $I \propto P/h\nu$, where h is the Planck's constant and ν the wave number of the incident radiation. Using this relation, the responsivity of the QED, in the visible region of the spectrum can be expressed as

$$I_{\text{qed}}\,[\text{A/W}] = \lambda\,[\text{nm}] / 1239.5 \qquad (1)$$

where λ is wavelength of the incident radiation.

Equation (1) is based on the assumption of one electron of photo current per incident photon because of the complete quantum conversion. The responsivity given by Eq. (1) determines the incident power on the detector absolutely. However, the linear responsivity is valid only in the wavelength range from 360 nm to 550 nm. At longer wavelengths, the responsivity drops without applied negative bias voltage. So, when using this detector at wavelengths between 550 nm to 800 nm without bias, it is desirable to determine the responsivity experimentally. This is done by calibrating the QED against the working standard photodiodes in the Vis/NIR SCF to provide traceability to HACR. Also, the maximum measurement range of the QED is limited to 1 μW to 50 μW without bias, and 1 μW to 2 mW with bias. It must be noted that the use of bias voltage can result in higher dark currents. The limited power range and its absolute measurement to a single wavelength of the incident flux makes direct application of QED difficult for calibrating heat flux sensors subjected to broadband radiation of several orders of magnitude larger in range.

For higher heat flux levels, cavity type electrically calibrated radiometers (Kendall and Berdahl, 1970) operating at room temperature serve as suitable transfer standards. These radiometers are water-cooled. The incident photon flux is nearly completely absorbed, to within a few fraction of a percent, by a cavity with multiple internal reflections. The electrical power required to produce the same temperature rise in the cavity, as the incident flux, is determined by measurement of voltage and current through a precision resistor. Considering the effective absorptivity of the cavity and other factors involved in electrical calibration, the measurements by ECR are likely to be within 0.5 % of the true value.

Depending on the heat flux level, different ranges of radiometers are required. To establish long term repeatability, it is desirable to maintain these radiometers calibrated with reference to a primary standard like a quantum efficiency detector. Presently, NIST uses a Kendall radiometer[2] of 4.2 W with an aperture area of 1 cm^2. The radiometer has a $1/e$ time constant of 6 seconds for a step change in irradiance. For large changes in heat flux level, it is necessary to allow about 60 seconds for stabilization before measurements are made. The manufacturer stated accuracy of this radiometer is 0.5 % of the true values, as determined by an experimental determination of the Stefan-Boltzmann constant.

Calibration of Heat Flux Standards

The measurements by an ECR are generally considered absolute. However, factors such as long term drift and cavity absorptance make it desirable to check the performance of the ECR with respect a primary radiometric standard at regular intervals. This is necessary to establish the long term repeatability and to increase the confidence level in the measurements. The range of a typical transfer standard ECR for high heat flux measurements is several orders of magnitude larger than that for the radiometric standard. This requires the use of an intermediate reference monitor whose calibration is linear from the low power level of the radiometric standard of about few μW to several watts power of the ECR, and a suitable transfer source to provide the required range of irradiance. A detector suitable for this purpose is a silicon photodiode whose output has excellent linearity with respect to incident light. The linearity of silicon photodiodes, over several orders of magnitude, up to fourteen decades, is now well established (Eppeldauer and Hardis, 1991). The NIST technique of transfer standard calibration uses a silicon photodiode mounted on an integrating sphere to sample a high power laser beam irradiating the transfer standard. The method and the experimental arrangement, described in detail in the next section, forms the first step in the transfer calibration of heat flux sensors.

Another radiometer which may be useful as a transfer standard is an ellipsoidal radiometer. The cavity of the radiometer head is an ellipsoid with the aperture at one focus and a thermopile detector at the other focus. The measurements by the ellipsoidal radiometer are not absolute and calibration with respect to a known blackbody source is necessary. Calibration with respect to a radiometric standard using laser irradiation is another possibility. However, this approach does not seem to have received much attention. The use of an ellipsoidal radiometer is cost-effective compared to an ECR, and can serve as a convenient transfer standard though less accurate than an ECR.

Calibration of Heat Flux Sensors

The transfer of calibration from the transfer standard ECR to the heat flux sensors is done using a broadband irradiating source as a blackbody. At NIST, a heated graphite tube cavity is currently used to provide irradiance levels up to 100 kW/m^2.

[2]Instruction manual for the Kendall radiometer system - Radiometer Model No. MK-IV, Serial No. 47601; Control unit Model No. 17601; by Technical Measurements Inc., La Cañada, CA.

This is a variable temperature blackbody (VTBB) source normally used in pyrometric measurements. The ECR and the sensor to be calibrated are located at the same fixed distance from the exit of the blackbody aperture. The VTBB is operated at different temperatures and the output of the sensors in mV, and the reading of the ECR in kW/m^2 which represents the heat flux level, are noted to determine the sensor calibration.

The methodology described above explains the various steps involved in the calibration of heat flux sensor traceable to U.S. primary standard, the cryogenic radiometer. In the present measurement chain, the QED-200 is used as a transfer standard rather than basic standard. In place of QED-200, QED-150 type trap which has a better dynamic linear range can be used. Also, the measurement chain can be shortened by using traps calibrated in the HACR. It is often the practice to employ the heat flux sensors calibrated by this approach as reference working standards to calibrate other sensors routinely used in applications using less expensive radiant heat sources.

EXPERIMENTAL ARRANGEMENT AND PROCEDURE

High Power Laser Facility

The transfer calibration test arrangement (Hunter and Walker, 1992) of heat flux sensors comprises of two experimental setups. The first setup, shown schematically in Fig. 2, consists of high power lasers and associated optics to

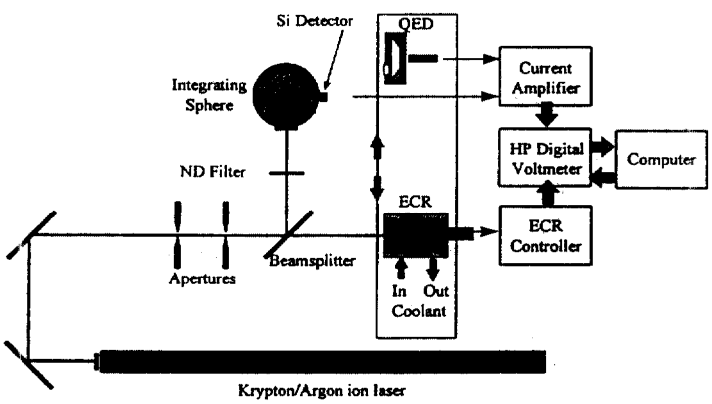

Fig. 2. High power laser setup for ECR calibration.

calibrate the transfer standard ECR. Two lasers, krypton and argon ion, lasing at 647.1 nm and 514 nm, respectively, provide the required level of irradiance at the sensors. The laser beam, reflected through two 45° mirrors and further defined by apertures, passes through a plate beamsplitter. The transmitted beam through the beamsplitter provides the irradiance to the primary standard quantum efficiency detector or the transfer standard ECR. The QED and the ECR are mounted on a precision traverse mechanism and can be moved to capture the transmitted beam from the beamsplitter. The QED and ECR apertures, each with an area of approximately 1 cm^2, are underfilled since the laser beam diameter is only about 1 mm.

The total power of the reflected beam from the beamsplitter is about 8 % of the incident beam. A silicon detector (Hamamatsu, Type No. S2281) mounted on an integrating sphere samples the reflected beam. The diameter of the integrating sphere is about 18 cm. The beam entering the sphere distributes uniformly on the inner surface of the sphere by multiple internal reflections. The output of the silicon detector is proportional to the strength of the reflected beam. Additional neutral density (ND) filters are used to reduce the power of the laser beam to keep the silicon detector output current within the saturation level. The krypton ion laser provides irradiance of up to 2.5 W at the transfer standard ECR. The argon laser is used for higher powers up to 8 W. Both lasers are operated in the single line mode to permit transfer of calibration from the primary standard QED to the silicon detector either using Eq. (1) or the calibration data from the spectral facility.

High Temperature Blackbody

The high temperature blackbody is used as a broadband transfer source to transfer the calibration from the transfer standard ECR to the heat flux sensors. Currently, this is being done using a Variable Temperature Blackbody (VTBB). Figure 3 shows the experimental arrangement used with the VTBB.

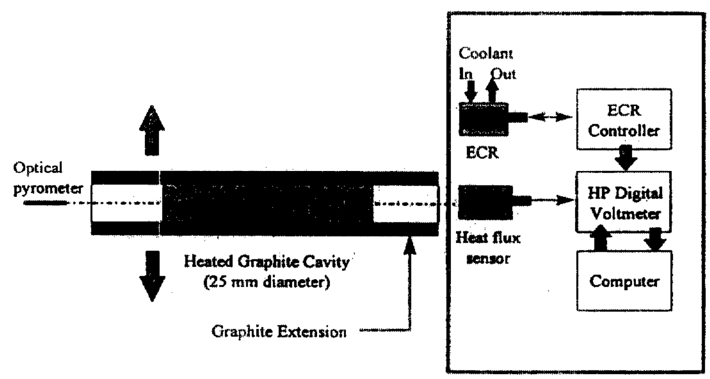

Fig. 3. Broadband calibration of heat flux sensor using VTBB.

This is a 25 mm diameter graphite tube cavity with a heated zone 14.1 cm long on either side of a center partition (3 mm thick). The electrical heating of the furnace facilitates rapid heating and cooling of the cavity. The furnace temperature is computer controlled in a closed loop and is measured by an optical pyrometer sensing radiation from one end of the tube. Depending on the temperature range, different filters are used for the pyrometer. The other end of the tube acts as the radiant aperture for the sensors and the transfer standards to be calibrated. To prevent sublimation at high temperatures and oxidation at low temperatures, the graphite tube cavity is purged with a continuous flow of argon gas (0.8×10^{-6} m^3/s). The temperature of the furnace is stable within 0.1 K of the set temperature. The entire blackbody assembly is mounted on a traversing mechanism, located in front of a work bench. The transfer standard ECR and the sensors to be calibrated are mounted on the workbench at a fixed distance from the blackbody aperture. While being heated to the required temperature, the blackbody assembly is stationed away from the sensors. After stabilization of the temperature, it is moved in front of the sensors to make measurements.

Test Procedure

First, using the laser facility described, a calibration between the primary standard QED and the silicon detector is obtained by operating the laser at low power levels. The photocurrent outputs of the QED and the silicon detectors, amplified by low-current amplifiers (Stanford Research Systems SR-570) are read by a digital voltmeter (Hewlett Packard, HP 3457A). Next, the transfer standard ECR is positioned to capture the transmitted beam and the laser operated at higher power levels to cover the full range of the ECR. The corresponding ECR and the silicon detector readings are noted. It must be noted that, with the laser beam, the ECR aperture is underfilled. Hence, the output reading of the radiometer control unit indicates the total heat flux absorbed by the cavity. For the particular ECR used in this calibration, the aperture area is close to 1 cm², and a reading represents the power in W/cm². To determine the calibration of the ECR, the readings of the silicon detector are converted to irradiance by using the calibration constant derived with reference to the QED,

The calibration of the heat flux sensors with respect to the ECR is done using the VTBB. The readings of the ECR and the sensor output in mV are recorded by operating the VTBB at different temperatures. In this case, the ECR aperture is overfilled and the ECR meter is pre-calibrated to read the power directly in W/cm². The measurements are done sequentially. The temperature of the VTBB is stable within 0.1 K of the set temperature over the test duration. The data acquisition for the laser and blackbody measurements is performed through a personal computer with an IEEE-488 interface.

RESULTS AND DISCUSSION

QED Characterization

To enable calibration of the transfer standard ECR using the krypton laser at 647.1 nm wavelength, the radiometric standard QED was first characterized in the Visible/Near Infrared Spectral Comparator Facility. The test was conducted in the wavelength range from 600 nm to 700 nm without bias voltage. Figure 4 shows the measured responsivity of the QED in this range. At 647.1 nm, specific to krypton laser operation, the responsivity was found to be 0.507 A/W. The uniformity across the QED aperture was better than 0.3 %.

ECR Calibration

Figure 5 shows a typical calibration of the ECR using the krypton laser. To account for the fluctuations in the laser power during measurements, readings of the QED, silicon detector, and the ECR were taken over a period of 60 s to 100 s, and the mean value calculated. This was considered necessary to account for the long time constant of the ECR. At 647.1 nm, the maximum measured power at the ECR was about 2.3 W. Using the calibration constant determined with reference to the QED, the silicon detector output signals were converted to determine the power level at the ECR. The corrected power at the ECR is plotted against the ECR indicated power in Fig. 5. The calibrations from three different sets of measurements show a high degree of linearity (R^2=0.999). Also, the calibration constant was found to be within 1 % of the results of the test conducted about a year ago. This repeatability increases the confidence level in the measurements and the expected linear behavior of the ECR.

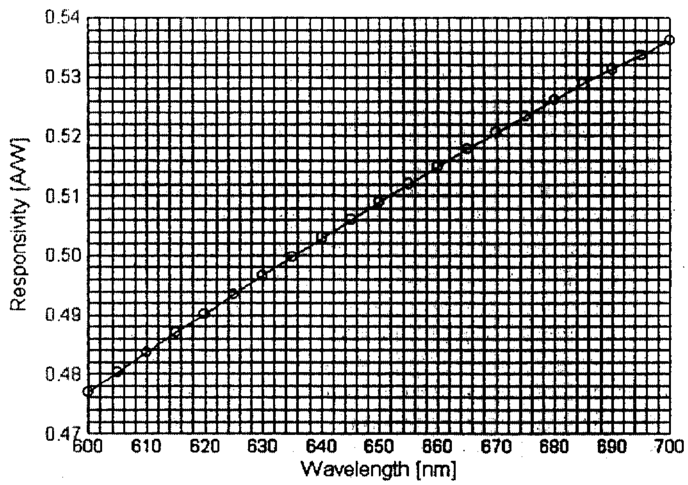

Fig. 4. Calibration of QED in the spectral comparator facility

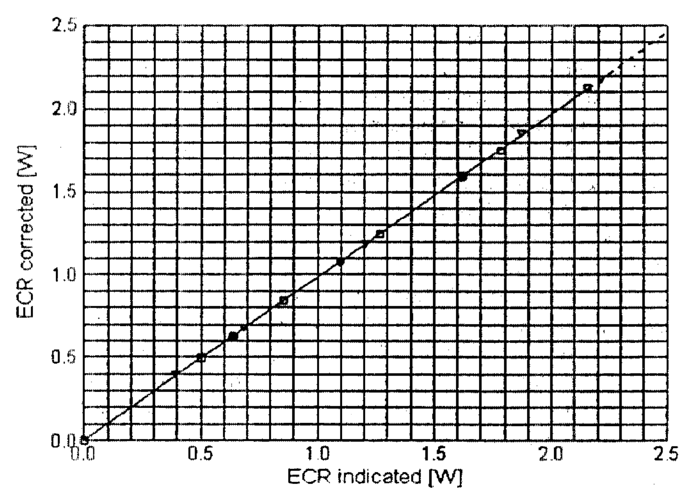

Fig. 5. Transfer standard ECR calibration using krypton laser.

Heat Flux Sensor Calibration

A Schmidt-Boelter heat flux sensor manufactured by Medtherm Corporation was calibrated with reference to the ECR using the VTBB. The Schmidt-Boelter sensor works on the principle of axial temperature gradient (Kidd and Nelson, 1995). The incident heat flux on the sensor surface flows axially, and the temperature gradient across a thin disk is proportional to the incident flux. The gage produces a self-generating thermoelectric voltage proportional to the temperature gradient and hence the heat flux. The sensor surface has a high emissivity (≈0.97) black coating, and the output of the gage is proportional to the net-absorbed heat flux at the surface, both convective and radiative. The sensor diameter is 4.8 mm and the body length 8.9 mm. For purposes of testing, the gage was mounted on a larger copper heat sink of 22 mm diameter. With the present experimental setup, the orientation of the gage sensor surface and the ECR aperture is vertical.

The required level of heat flux at the sensor surface can be obtained either by locating the sensor close to the exit of VTBB and operating at lower temperatures, or away from the exit and operating at higher temperatures. In principle, the two situations should give identical calibration results provided other secondary effects are small in comparison with the radiant heat flux of the blackbody. One particular concern with the operation of the VTBB is the influence of the argon gas used for continuous purging of the cavity. Assuming the total gas flow is uniformly distributed on two sides of the cavity partition, the average velocity of the exit flow is about 0.08 m/s. When the sensor is located close to the exit of the cavity, the low velocity jet exiting from the cavity impinges on the sensor surface and can affect local heat transfer. This effect is likely to be reduced when the sensor location is moved away from the exit, due to decay of the jet flow. However, away from the exit, the level of the radiant heat flux also is reduced, and to maintain the level of heat flux, it is necessary to increase the temperature of the blackbody.

A quantitative estimate of the effect of the argon flow can be quite complex. Hence, to examine the influence of the argon jet flow on sensor calibration, experiments were conducted by locating the sensor and the ECR at two different locations from the VTBB exit but covering the same range of heat flux by operating at different temperatures. Figure 6 shows the variation of the deviation from mean values of the ECR and sensor signals with time for three levels of heat flux, approximately 10 kW/m², 20 kW/m² and 40 kW/m². The recording of the data was initiated after about 60 s after moving the heated VTBB in front of the ECR to allow for the long time constant. The location of the VTBB from the ECR and the heat flux sensor was 62.5 mm. At the lowest heat flux level of 10kW/m², the ECR output shows a gradual increase of about 0.2 % of the mean value. Also over a period of 100 s, the readings of the ECR show a slow heating and cooling of the cavity about the mean value. The fluctuations in the argon gas jet flow are more apparent in the output of the Schmidt-Boelter heat flux sensor due to its relatively lower time constant of about 50 ms. The fluctuation from the mean is about 0.2 % of the mean value. While the same trend is observed at the higher power of 20 kW/m², the effect becomes smaller at the higher heat flux level of about 40 kW/m².

Figure 7 shows the corresponding variations in the ECR and heat flux sensor signals at approximately the same heat flux levels, when they are located close to the exit of VTBB, about 12.5 mm from the cavity extension. At the lowest heat flux of about 10 kW/m², the fluctuations in both the ECR and the heat flux sensor output are much larger than when located away from the exit (Fig. 6). The unsteadiness in the argon jet flow is apparent from the sensor output. It appears that the argon gas causes a sudden increase in the heat flux level at the sensor surface by as much as about 1 % of the mean value followed by cooling cycle which lasts for several seconds. These effects remain at the higher heat flux levels but the magnitude as a percentage of the mean become lower. At the higher heat flux level of about 40 kW/m², the fluctuations are within about 0.2 % of the mean value.

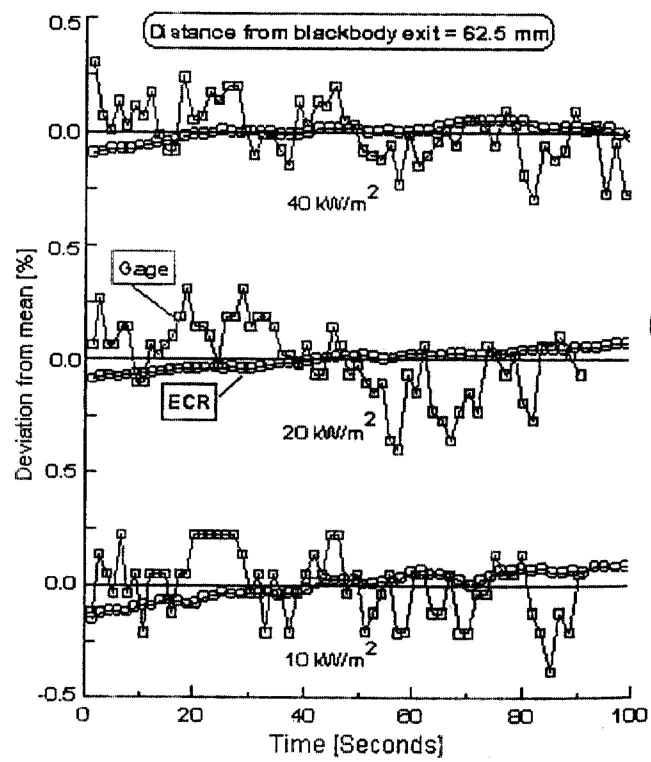

Fig. 6. ECR and heat flux sensor output variation with time. (Location from blackbody exit = 62.5 mm)

Figure 8 shows the Schmidt-Boelter sensor calibration obtained from the mean values of the ECR and sensor signals output. Despite the relatively larger effect of the argon gas flow on the ECR and the sensor when located close to the exit, the mean values still show excellent agreement with the linear calibration obtained when located farther from the VTBB exit. The corresponding variation of the calculated standard error with increasing heat flux is shown in Fig. 9. The effect of the n jet flow decreases considerably above heat flux levels of about 20 kW/m².

In addition to change in jet flow effects, the temperature range of the VTBB required to obtain the same level of heat flux at the sensor surface will be higher when it is farther from the exit. Hence, for the same heat flux level at the sensor, the spectrum of the blackbody radiation will be different for the two cases. The close agreement in calibration between two positions of the sensor suggests that the sensor surface coating has almost a gray or wavelength independent emissivity. Separate emissivity characteristics (Jones, 1996) of the optical black coating show the average absorptance over the wavelength range 0.2 μm to 20 μm to be 0.96.

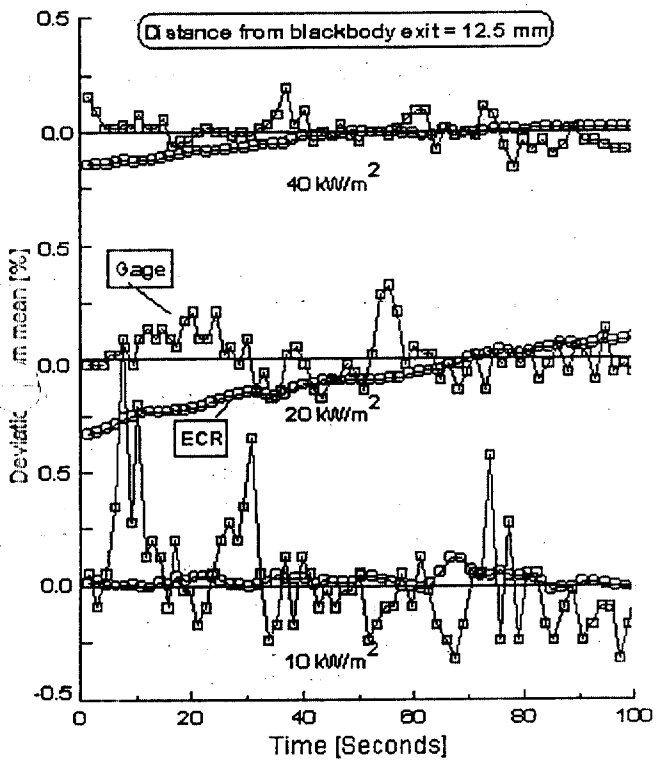

Fig. 7. ECR and heat flux sensor output variation with time. (Location from blackbody exit = 12.5 mm)

Calibration Uncertainties

With transfer of calibration at various stages, the uncertainties in measurements add up. Table 1 shows the estimated uncertainties (Taylor and Kuyatt, 1994) for one of the gages tested. Part I refers to the measurements during transfer standard calibration, and Part II, during gage calibration using VTBB. The measurements discussed in this paper and the calibration of other sensors with the present setup, show that the total uncertainty in calibration of heat flux sensors is about 1.4 % (k = 2). These are accrued mainly in the calibration of ECR using the laser and the broadband calibration using VTBB. Calibration uncertainty of the QED is much smaller and is about 0.2 %. When calibrating the heat flux sensors in the range up to 20 kW/m², particular attention must be paid to the effects of argon jet flow in the VTBB.

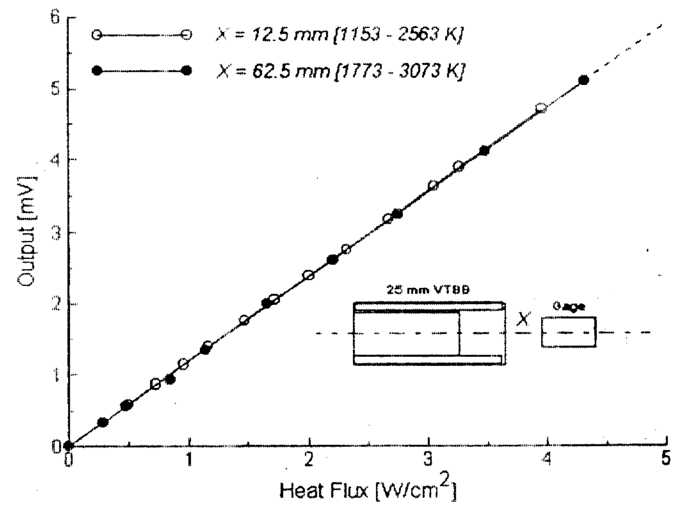

Fig. 8. Calibration of Schmidt-Boelter gage at two locations from 25-mm VTBB exit.

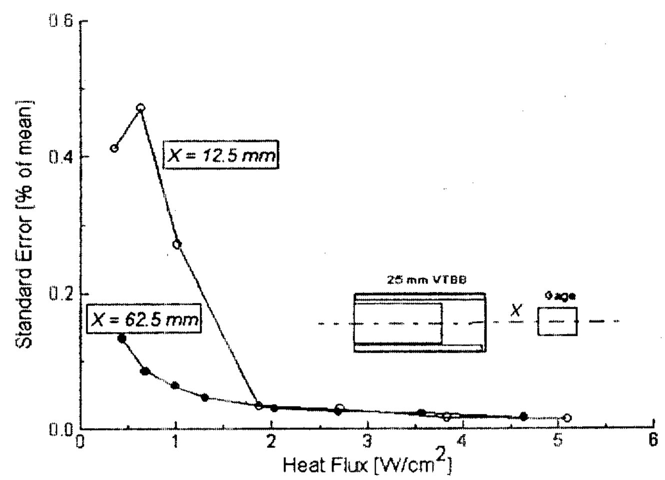

Fig. 9. Variation of standard error in measurement with heat flux for two gage locations.

Heat flux measurements in practical applications such as fire research and convection heat transfer, using heat flux sensors have been the most elusive often with large uncertainties introduced both during calibration and/or application environment. Uncertainties in final measurements or calibration of 3 % to 5 % are not uncommon. The objective of the present methodology is to develop, improve and maintain standards for heat flux measurements to achieve a much reduced level of uncertainty of about 1 %. With extensive testing of various gages and the ECR, it is planned to achieve this goal. Alternative approaches (Murthy et al.), such as an "absolute technique", performed in parallel will be necessary to develop full confidence in the technique.

Table 1. Estimate of uncertainties [%]

Uncertainty source	Type	Uncertainty
Part I:		
QED calibration	B	0.2
Silicon Detector reading	A	0.2
ECR reading	A	0.1
QED-SiD transfer	B	0.2
SiD-ECR transfer	B	0.4
Part II:		
Alignment	B	0.4
ECR reading	A	0.1
Gage reading	A	0.2
Relative Expanded Uncertainty	**k = 2**	**1.4**

FURTHER WORK

To extend the technique to higher power levels, the transfer technique requires a suitable range ECR. The availability of cavity type electrically calibrated radiometers for high heat flux levels is at present limited. NIST is planning to use a higher range ECR suitable for calibration up to 200 kW/m². A high temperature graphite tube blackbody with a maximum temperature of 3200 K, and a 28 mm tube diameter will be used developed to calibrate higher range heat flux sensors by broadband radiation. Some of the results of argon gas flow effects studied in the VTBB will be useful in implementing the technique with the high temperature blackbody. Further tests are planned in a spherical blackbody with a 50 mm diameter radiating aperture and a maximum temperature of about 1400 K. The calibration can be carried out under ambient conditions with reduced convection effects with this spherical blackbody because of no purge gas effects.

CONCLUSIONS

The methodology for calibrating heat flux sensors using transfer calibration technique with traceability to the NIST High Accuracy Cryogenic Radiometer is described. Plans to implement the technique for calibrating the sensors up to 200 kW/m² are in progress. Preliminary results from calibration of a transfer standard ECR using laser radiation, and calibration of a Schmidt-Boelter gage using blackbody radiation are presented. The results of Schmidt-Boelter gage calibration, located at two different distances, show good agreement within the measurement uncertainty of 1.2 % ($k = 2$).

ACKNOWLEDGMENTS

The authors wish to thank Robert Saunders, Optical Technology Division, NIST, for support and encouragement of this work. The authors also wish to acknowledge William Grosshandler and Ken Steckler from the Building and Fire Research Laboratory at NIST for useful discussions.

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